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Ion Implantation of ^3He in Tantalum for Use in a Low Energy Deuteron Polarization Analyzer

(Rough Draft, Last Update 21MAR94)

Andrew C. Hird, K. A. Fletcher, E. J. Ludwig, Z. Ayer

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The implantation of tantalum foils with ^3He has been accomplished for implant energies from 7 to 20 keV and doses from 1.5-29.3 Coulombs/cm^2. Implant thicknesses are not consistent with the Zero order implantation theory, but are in agreement with previous experiment. Thickness dependence upon implant energy, dose, and temperature are studied. The foils were bombarded with deuterons to determine target thicknesses, thickness lifetimes, and to study the properties of the tensor analyzing power of the $^3He(\vec{d},p)^4He$ reaction near its 430 keV resonance [1]. A_{yy} is measured and appears energy independent and isotropic in the energy range 222-322 keV.

The $^3He(\vec{d},p)^4He$ reaction at low incident energies is important in nuclear fusion and astrophysics. Its properties also suggest its use as a low energy deuteron polarimeter with a very good efficiency [TUNL Prpsl],[3]. Previously, the reactions $^3H(\vec{d},n)$ and $^2H(\vec{d},p)$ have been used in the energy region below 1 MeV, but the neutrons from the tritium reaction are difficult to detect and the cross section of the $^2H(\vec{d},p)$ reaction is low and anisotropic. The efficiency for analyzers depends on $\sigma A_{zz}{}^2$ where σ and A are the cross section and analyzing power, respectively. The cross section of the $^3He(d,p)$ reaction below 978 keV appears isotropic to within $\pm 5\%$, and is large so that the efficiency of this reaction exceeds that of the deuterium polarimeter above 100 keV [1] (Figure 1). There is virtually no data for this reaction available in the region of importance to nuclear fusion and astrophysics. $T_{20}(0^o)$ at 240 keV [2] and at 340 keV [3] and $T_{20}(\theta)$ at 340 keV [4] are the only existing analyzing power data. Thus a comprehensive study of the analyzing power of $^3He(\vec{d},p)$ would be beneficial, and could give us an analyzer with a higher efficiency than the currently used reactions.

Gas cells are not suitable targets at low energies because of large energy loss and straggling of the incident deuterons penetrating the cell walls. The typically inexpensive options are ion implanted targets or evaporation of a compound including the target gas on a thin foil. There are several

complex and expensive alternatives such as cryogenic targets and gas jets. For noble gases ion implantation is the only alternative. Furthermore, implantation facilities are available without modification and target making is fairly fast, reproducible and inexpensive. Implanted foils are easily handled and stored and some experimental information about preparation already exists. Also, implants are in the surface layer (in this case within 72 nm) and models exist to determine a cross section of the implant [18].

Tantalum foil was chosen as the best host material based upon a theoretical comparison of saturation thicknesses calculated using the C code "thick.c" (Appendix B) which uses the zero order approximation[5], [6]. This approximation of saturation thickness assumes that the maximum retained dose depends only on sputtering [3],[16].

The saturation target thickness, W, to zero order is

$$W[\frac{g}{cm^2}] = \frac{M\rho R(E)}{m(S(E)+1)} \tag{1}$$

where S(E) is the sputtering rate in number of atoms sputtered per ion at energy E, M and m are the target mass and ion mass respectively. The substrate density, ρ, is in grams per cm^3. R(E) is the LSS Projected Range (for Linhard, Schieott, and Scharff) in cm, tabulated in Ziegler's books on ion implantation is solids [7], [22]. R(E) is calculated for ^4He in [7] for the energy range of our implanter. Ziegler states that no simple relationship exists to convert ^4He ranges to ^3He ranges, but ^3He ranges are generally larger for energies less than 1 MeV [7]. Calculations using Ziegler's monte carlo simulation of implantation TRIM [18] indicates that the ranges of the two isotopes are roughly equal.

The theory describing the sputtering ratio S(E) is detailed in reference [6], and is given by

$$S(E) \approx 4.24 \times 10^{-10} n_o R^2 E \frac{M_1 M_2}{(M_1 + M_2)^2} \exp(-10.4 \frac{E_B \sqrt{M_1}}{M_1 + M_2}) \quad (\#atoms/ion) \tag{2}$$

where E_B is binding energy in eV of substrate atoms from refs. [8], [14], [15]. The incident ion energy, E, is in eV. M_1 and M_2 are mass numbers of ion and target atoms, respectively. The target density, n_0, is in atoms per

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m^3. R is collisional diameter (in meters) related to mean free path by

$$\lambda = \frac{1}{\pi R^2 n_o}$$

and describes the slowing down of an ion in a screened Coulomb field of a type proposed by Bohr [19].

$$R = \frac{a_o}{Z_1^{2/3} + Z_2^{2/3}} \ln\left(\frac{Z_1 Z_2 (M_1 + M_2)}{REM_2} \frac{e^2}{4\pi\varepsilon_o}\right) \tag{3}$$

where $\frac{e^2}{4\pi\varepsilon_o}$ is the fine structure constant (1.439976×10^{-9} eVm), a_o is the Bohr radius in meters, Z_1 and Z_2 are the atomic numbers for ion and target atoms, respectively.

The program "thick.c" (Appendix B) iterates equation (3) in a similar manner to the FORTRAN subroutine Sputterrate.for [8] and calculates the same results for R. "Thick.c" then calculates S(E) and the saturation thickness W(E). As a test of the program, "thick.c" results for S(E) for ^4He on Tantalum were found to match those of Sputterrate.for and the experimental results for ^{20}Ne implanted in several substrates by Almen and Bruce were found to be within 40% of the calculated values from "thick.c" [6]. Therefore the calculation for S(E) is within an order of magnitude of experiment. "Thick.c" displays all the input variables and calculated results. Thick.c's calculated theoretical saturation thickness for ^4He on Tantalum at 45 keV was found to be 2×10^3 larger than obtained experimentally by Cole and Grime [9] and similarly larger than our experimental results. Comparison of zero order predictions with experimental values indicates that unreasonably high sputtering yields are needed to explain there results [5], [17].

It is important to understand the characteristics of implantation in this experiment that deviated from the assumptions made in the zero order approximation. The Zero order approximation neglects range shortening, diffusion due to stress or temperature, changes in sputtering rate, and back scattering of incident ions. Range shortening occurs when the density of collected ions begins to contribute to the stopping of injected ions [11]. In the range of a 20 keV ^3He in Tantalum (72 nm) there are approximately

$4x10^{17}$ Tantalum atoms/cm2 and therefore range shortening by ^3He thicknesses of the same order of magnitude could be a factor in the stopping if additional implanted 3He ions. However the larger Tantalum atoms certainly contribute to most of the stopping. References [10] and [11] state that this effect is of minor importance for the near surface implants under study. After a certain limiting concentration of implanted ions, stress-induced variations in the target atom's binding energy begin to allow considerable loss of ions previously implanted. This is most significant in low energy implants when the concentration is in the near surface region (<300 Angstroms) [11]. The ranges of ^3He ion implanted in Tantalum at 7 to 20 keV are from 300 to 700 Angstroms [18] and so it is possible that stress induced out diffusion is a dominant effect in ^3He retention. Cole and Grime describe a blistering effect where the very mobile He atoms migrate to lattice defects and eventually form high pressure gas blisters [9]. When these burst, large amounts of implanted material is lost. They found this to occur after 10-12 hours of 5 $\mu A/cm^2$ He ions at 60 keV (a dose of about 0.22 Coulombs/cm^2). Thermal diffusion can also occur during implantation under the elevated temperatures of intense ion bombardment. The difference in the diffusion constant of a heated foil (approx. 800°K) and a cooled (approx. 100°K) foil is a factor of 10^{16} [9]. However, for krypton implanted in Tantalum, no diffusion was observed by Almen and Bruce up to 600°C and therefore temperature stability of implants in Tantalum may be of minor importance [6]. Thermal diffusion during storage may also play a role in limiting target thickness, but in refractory metals such as Tantalum the implants are relatively permanent at temperatures below 150° C [6]. The theoretical sputtering rates used were applicable to ions implanted at normal incidence. The tantalum foils used were not flat and sputtering during implantation erodes the surface. Sputtering experiments at oblique angles indicate that at larger angles the sputtering rate increase [6]. Therefore the average sputtering rate could very well be larger than S(E) at normal incidence. TRIM calculations also indicate that a substantial percentage of incident 3He ions may be back scattered [18].

The theoretical saturation values were calculated for 8 keV ^4He ions on various substrates Tantalum, Tungsten, Carbon, Molybdenum, Platinum, Gold, and Titanium. Tantalum was found to have a zero order predicted

saturation thickness 2.4 x 10^{20} atoms/cm^2 which is rivaled only by Pt and Au. Tantalum foils of thickness .05 mm were chosen because of their relative low cost and availability.

Target Production

The General Ionex Sputterbell was used as an implanter[8], [20],[21]. It provides a maximum beam energy of 20 keV and experience has shown it capable of greater than 8 mA at this energy using singly charged ^{3}He ions. Operation of the system is well described in ref. [8]. The system consists of an ion source, beam extraction electrode, and an Einzel lens for focusing the beam on the substrate foil (Figure 2). After leaving the lens the ions travel approximately 14 cm and impact the target substrate at normal incidence. The substrate is mounted on an insulated cold finger, cooled with liquid nitrogen, where the beam current is collected (Figure 3). Target implantation data are given in Appendix A. In general, the beam was defocused to prevent the substrate from visually glowing, the energy of implant was kept constant and the maximum cooling available was used. Time and beam current were recorded and the resultant dose was calculated. Substrate mass was measured before and after implant with a Mettler micro-balance to calculate sputtering ratios.

Target Testing

Targets thicknesses were measured with both low and high energy deuteron beams at Triangle Universities Nuclear Laboratory (TUNL). The detectors used in this study were 1000 or 2000 μm silicon surface barrier detectors with solid angles of 0.4 mStr for high energy and 10 mStr for low energy tests. Initially, tantalum foils were implanted with ^{4}He doses of 4×10^{19} ions/cm^2 and tested with Rutherford back scattering of 3.03 MeV protons. No ^{4}He was detected above the background putting maximum implant at 10^{17} ^{4}He/cm^2. Much later, it was realized that this should have been expected since Cole and Grime's best ^{4}He implant in Tantalum at a larger implant energy was 5×10^{17}/cm^2 and would be barely visible in the noisy spectrum.[9]

Next, tantalum foils were implanted with ^{3}He and bombarded with 4 and 5 MeV deuterons. Detectors were placed at a lab angle of 130°. It was

expected that the 18 MeV protons from the $^3He(\vec{d},p)^4He$ reaction would be more visible. The statistics were poor, but a definite implant in all the targets on the order of 10^{17} $^3He/cm^2$ was found (Figure 4, targets Ta#11 and 12). Implants in tungsten, Havar and carbon were also tested. An extended measurement for target thickness lifetime during bombardment at 4 MeV was made using Ta#17 as shown in Figure 5. After this test, one of the targets was bombarded with low energy deuterons and a very clean spectrum of protons was found (Figure 6) indicating that future tests should done closer to the 430 keV resonance for $^3He(\vec{d},p)^4He$ where additionally the cross section is isotropic.

Low energy tests were accomplished using the Low Energy Beam Facility (LEBF) and lab energies up to 322 keV, lab angles between 10° to 65° and 300 to 400 nA beams. An unusual result was found for Ta#21 that deserves further investigation. This target had the largest thickness found of 2.6×10^{17} $^3He/cm^2$, but was implanted with the smallest dose. An extended measurement of target thickness lifetime during bombardment at 322 keV, 300 nA was made using Ta#25 as shown in Figure 7.

In the last test of this series, measurements of the tensor analyzing power, A_{yy}, below the resonance were made to explore the isotropy of A_{yy} and its energy dependence. The thickest targets from previous runs were used to increase statistics. Beam polarization for two states #2 and #3 (state #1 was unpolarized) was measured at 7 MeV using the tandem accelerator and a polarimeter using the $^3He(\vec{d},p)^4He$ reaction. (Figure 8) During the experiment P_{zz} was measured at the beginning, and twice during the tests. One pair of right and left detectors were fixed at 10°, where another pair of movable detectors allowed measurements at various other angles.

Discussion

Measurements with high and low incident deuteron energies yield similar results for target thicknesses. As predicted by reference [6], higher implant energy tended to produce thicker targets (Figure 9). Target thicknesses were found to be three orders of magnitude smaller than the zero order approximation predicted. It is interesting to note that the relative differences in theoretical saturation values is similar to the relative differences in averaged measured thicknesses (Figure 4). This

raises the possibility that the saturation value has been reached at a much smaller value than the calculated values. Recall the earlier mention of the target made with the smallest dose at 17 keV was found to be the thickest one made in the entire study. Also remember the blistering that Cole and Grime observed for 60 keV ^{4}He ions at doses larger than .22 Coul/cm^2 [9]. All targets made in this study well exceeded this implant. Even the thickest target mentioned above had over six times Cole and Grime's approximate blistering dose. The evidence strongly suggests that in all targets produced, doses exceeded the blistering dose for ^{3}He on Tantalum. With the typical implant beam currents used, this dose was exceeded in about 2 minutes of implant (assuming 100% efficiency). Continued bombardment with ions resulted in a decrease of implant thickness as seen in Figure 10 for targets implanted at 17 keV. At first it was thought that this was due to the blistering effect previously mentioned. Using the Atomic Force Microscope [23] it became apparent that this was not the complete explanation. Sputtering damage to the targets' surfaces was severe and no blistering phenomena was observed (Figure 11). From these pictures it also is obvious that implanted ions do not encounter a flat surface. The increased sputtering rates due to oblique angles of incidence could promote the loss of previously implanted ^{3}He[6]. However, Almen and Bruce found that after sputtering away approximately 200 μg/cm^2 of Tantalum with 45 keV Krypton ions that the sputtering rate became relatively constant [6]. All the ^{3}He implanted targets made in this study had mass losses from sputtering larger than 200 μg/cm^2 and therefore the sputtering rate is probably relatively constant.

The results from the AFM images suggest a possible description of how the sputtering that occurred during target production limited the retained quantity of ^{3}He. As the incident ions whittle away at the substrate surface they bore into previously implanted regions of ^{3}He, sputtering away the implanted ions as a result. No increase in implant thickness can then occur as the implant continues and as shown already in Figure 10 it seems that continued bombardment only lowers the saturation value. As a simple test of this postulate consider the problem shown in figure 12 of determining the depth of the hole that sputtering has produced.

It appears that not only was the blistering dose exceeded during target production, but also that a drilling process due to sputtering has begun to occur inhibiting any addition to the retained 3He. The effects of blistering and range shortening are hidden by this overwhelming process.

The lifetime data for ^3He targets observed under 4 MeV, 200 nA and 322 keV, 320 nA deuteron beam were shown in Figures 5 and 7. The diffusion is much lower under the 322 keV beam. The best fit to the data is a steep exponential fall off as the surface layer is blown off, followed by a slow decrease in thickness where the thickness only changed by 2%. In contrast, in less than half the incident charge the loss with 4 MeV deuterons resulted in a 21% decrease in thickness. The effect of a thick surface layer blowing off is not observed and perhaps happened too quickly to see. As suggested by Cole and Grime cooling of the foil during testing and use should decrease this diffusion rate. Observance of the diffusion effects of storage at STP are not well known but appear to be very small for tantalum targets. If the saturation thickness for these Tantalum targets is actually on the order of 10^{17} $^3He/cm^2$ then the implants would seem relatively permanent at STP. Diffusion during the elevated temperatures of implant can be seen in Figure 13. The two targets Ta#23 and #25 while being implanted has a sizable spot in the implanted area that was visually glowing. That spot was tested separately and labeled with a H (for "Hot"). In both cases the hotter portion of the targets has less of an implant.

The substrates W, C, and Havar showed no advantage over Tantalum targets of the same age with regards to implant thickness (Figure 14), however these targets were all 11 weeks old. The different elemental diffusion rates during storage may have played a factor in this result. The doses in these substrates were not equal, but were made with as large a dose as was practical to maintain a visually cool substrate. Regardless of these factors, for production purposes tantalum appears to be the superior of the four substrates.

A_{yy} was measured in the $^3He(\vec{d},p)^4He$ reaction for two polarization states mentioned earlier. State #1 was unpolarized. P_{zz} for state #2 was 0.638+-.021 and for state #3 was -0.671+-.007 (Figure 8). These P_{zz} data must be taken as an upper limit to the P_{zz} in the test chamber. This is due to the larger beam aperture in the test beam compared to the smaller aperture in

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2. I request clearance as soon as possible. Submission for publication is planned for no later than 1MAY94. Thank you for your consideration.

A. C. Hird, 1Lt, USAF
Student, Air Force Institute of Technology
Chapel Hill, NC

the beam where P_{zz} was measured. The spin substate mixing effects of axial magnetic field gradients cause depolarization of off axis deuterons traversing a cylindrical symmetric magnetic field. [12] However any significant depolarization would cause a deflection of the depolarized particles while passing through steering magnets and thus would never reach the target. The measured data indicates an isotropic and energy independent tendency in A_{yy} as shown in Figure 15 which is the averaged A_{yy} of both polarized states vs. angle.

Suggestions

Future production of ^{3}He targets should be made at lower doses (perhaps lower than 1 Coulomb/cm^2) than in this study. It appears doses of 1.5 Coul/cm^2 are greater than the saturation value for ^{3}He implanted in tantalum. A template could be designed to make multiple targets and control the implant area. A possible design would be an insulating template sandwiched between a grounded conducting template and the substrate. The accuracy of measuring beam currents could be improved by using a well calibrated beam current integrator. As seen in this study and the references, cooling of the foil and maximum implant energy should be used to maximize target thicknesses.

Conclusion

The ^{3}He($\vec{d}$,p) reaction is a practical improvement to the current deuteron polarimeters in use in the regime near its resonance and greater than 100 keV. The isotropy of the cross section and analyzing power should also improve accuracy and speed of polarization measurements. Further study of ^{3}He implantation of Tantalum at lower doses is warranted to increase target thicknesses and reduce production time and expense.

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Appendix A Target data
Appendix B Thick.c

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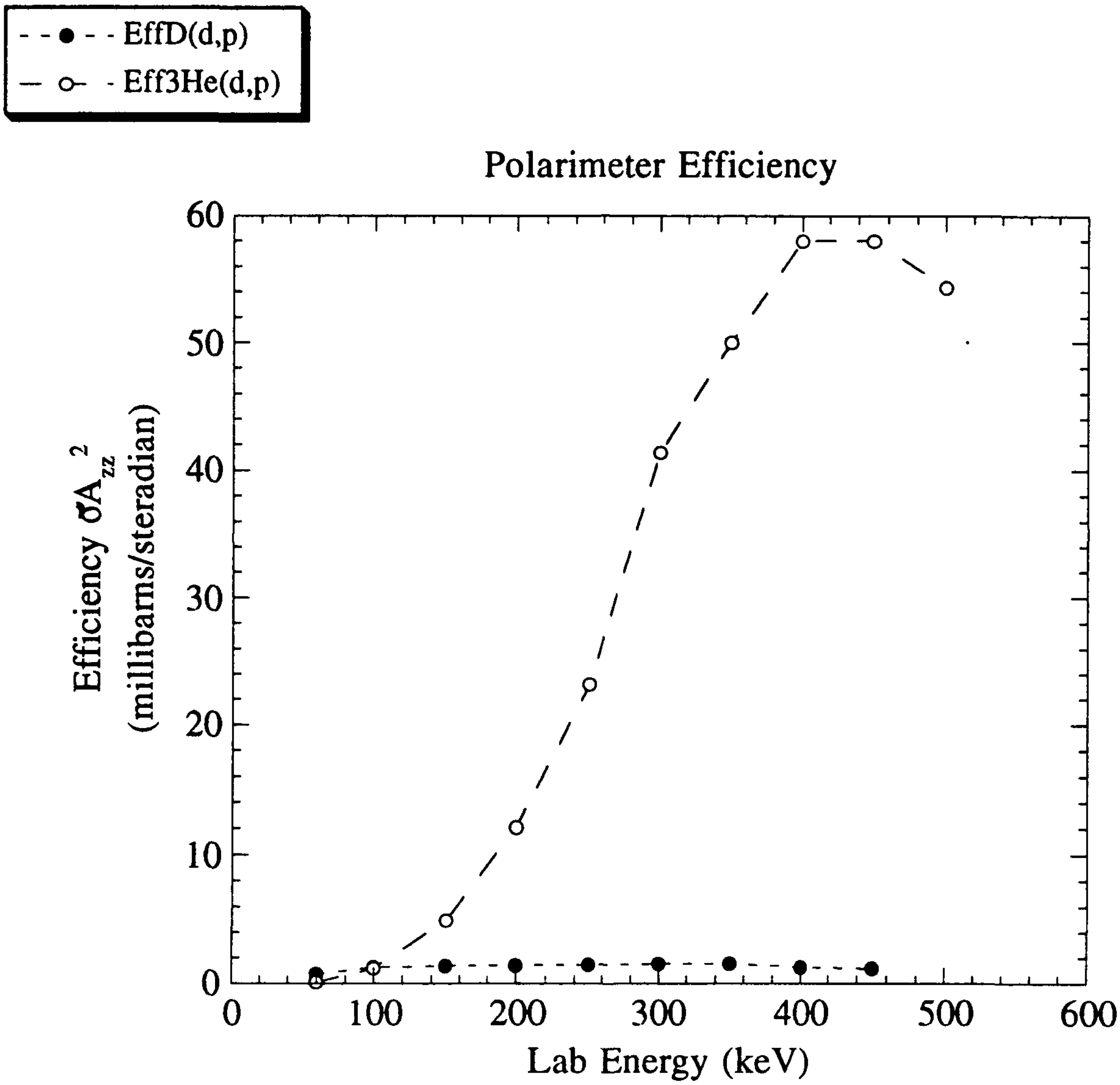

Figure 1 (data from [1], [13])

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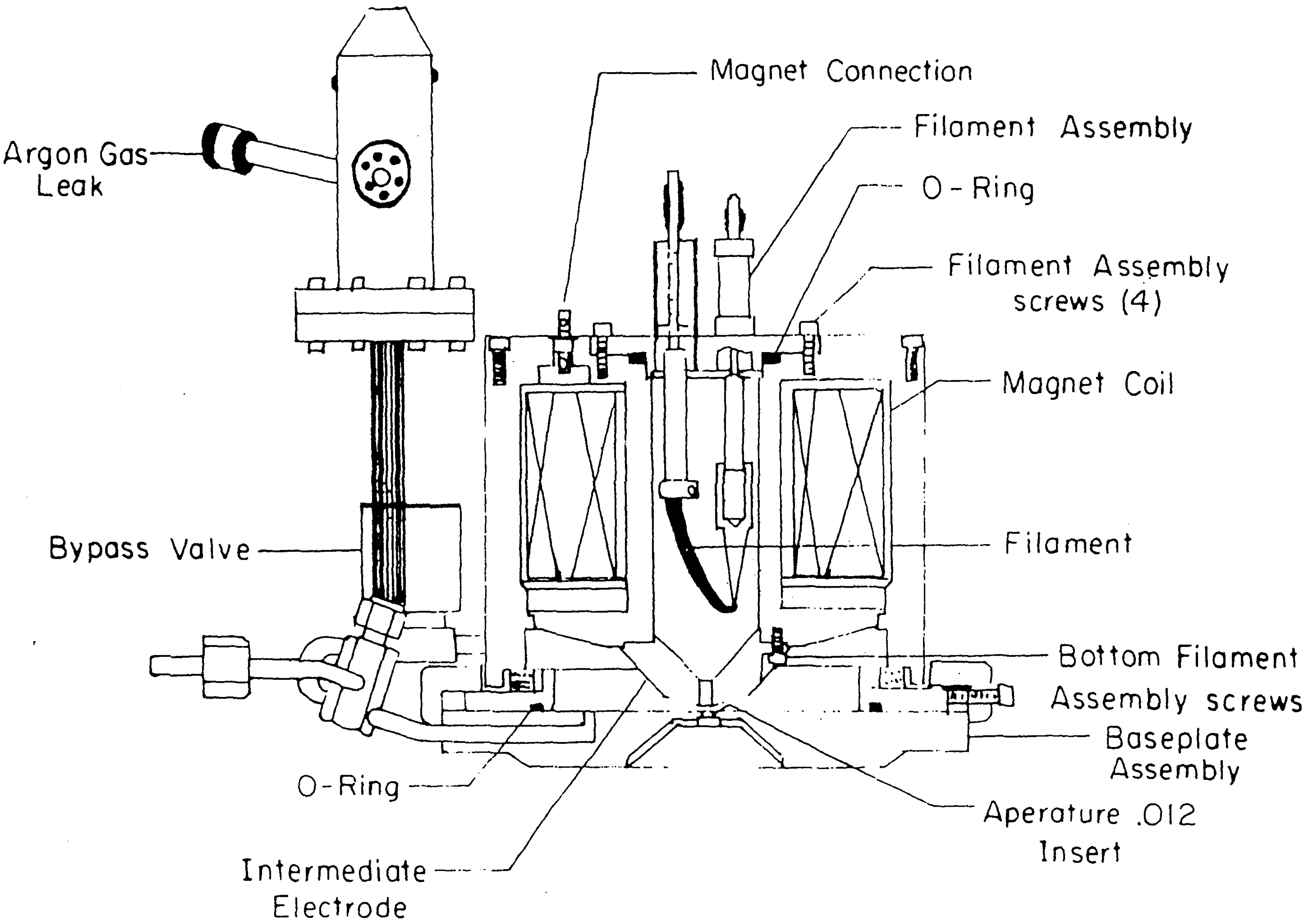

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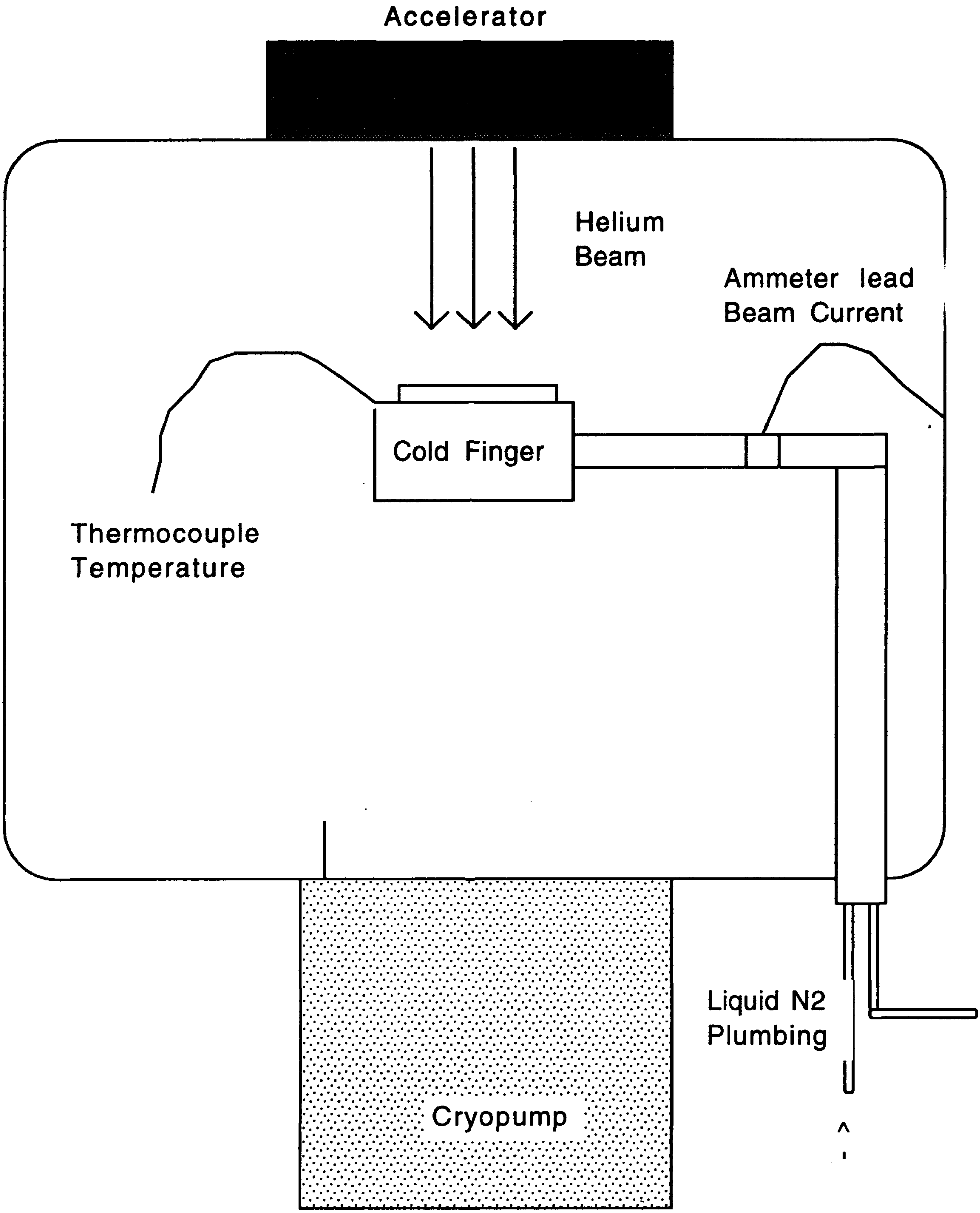
FIG 2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Ammeter lead
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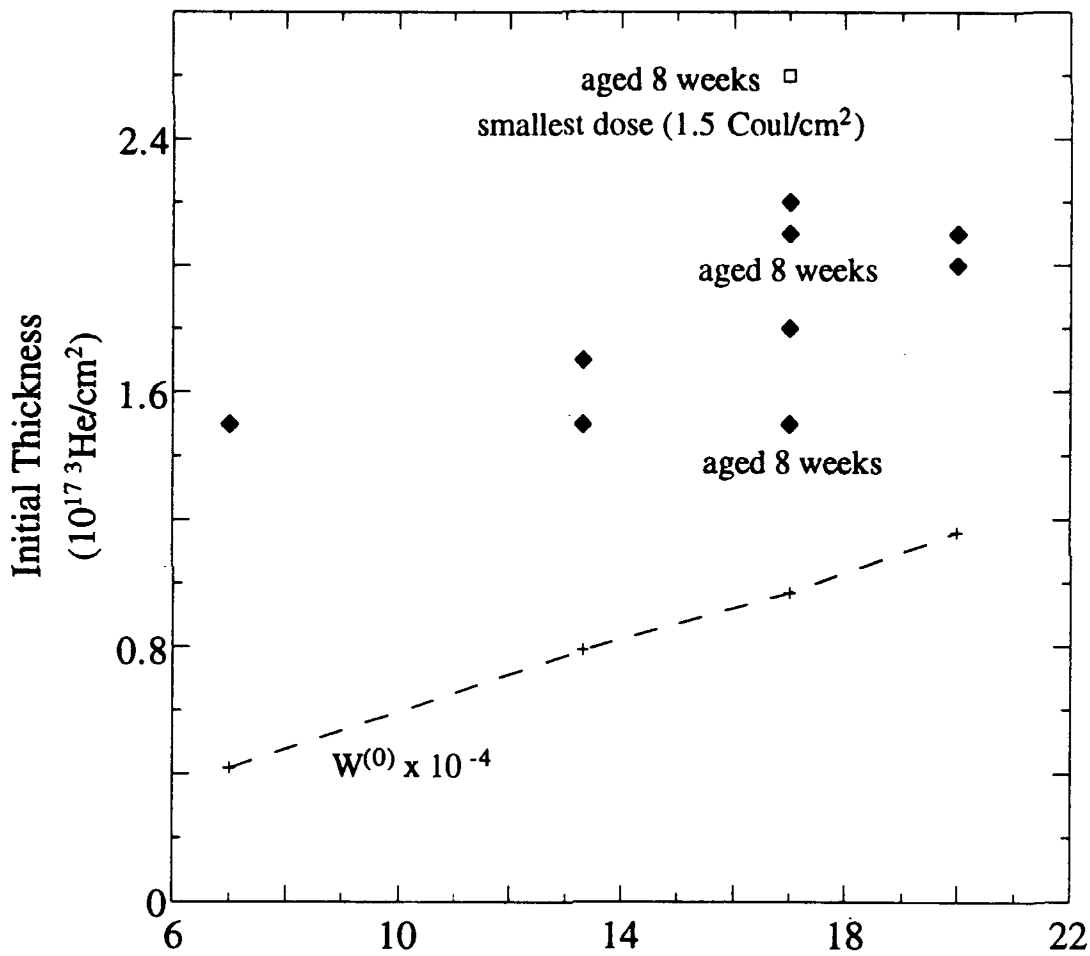
Figure 3

Initial Target Thicknesses



Energy (keV)
Error bars have been suppressed for clarity, all are less than 10%
See Appendix A

Figure 4

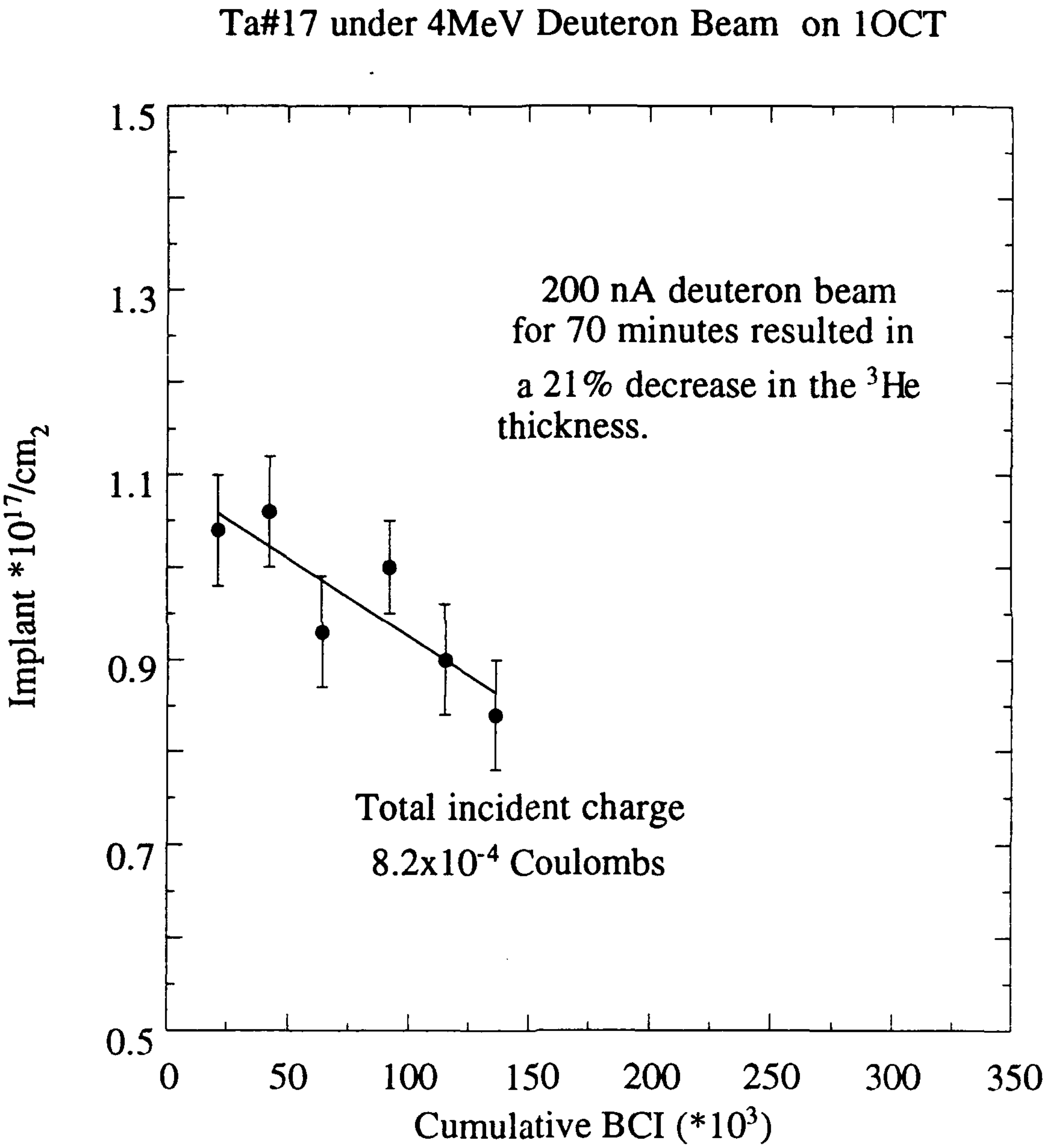
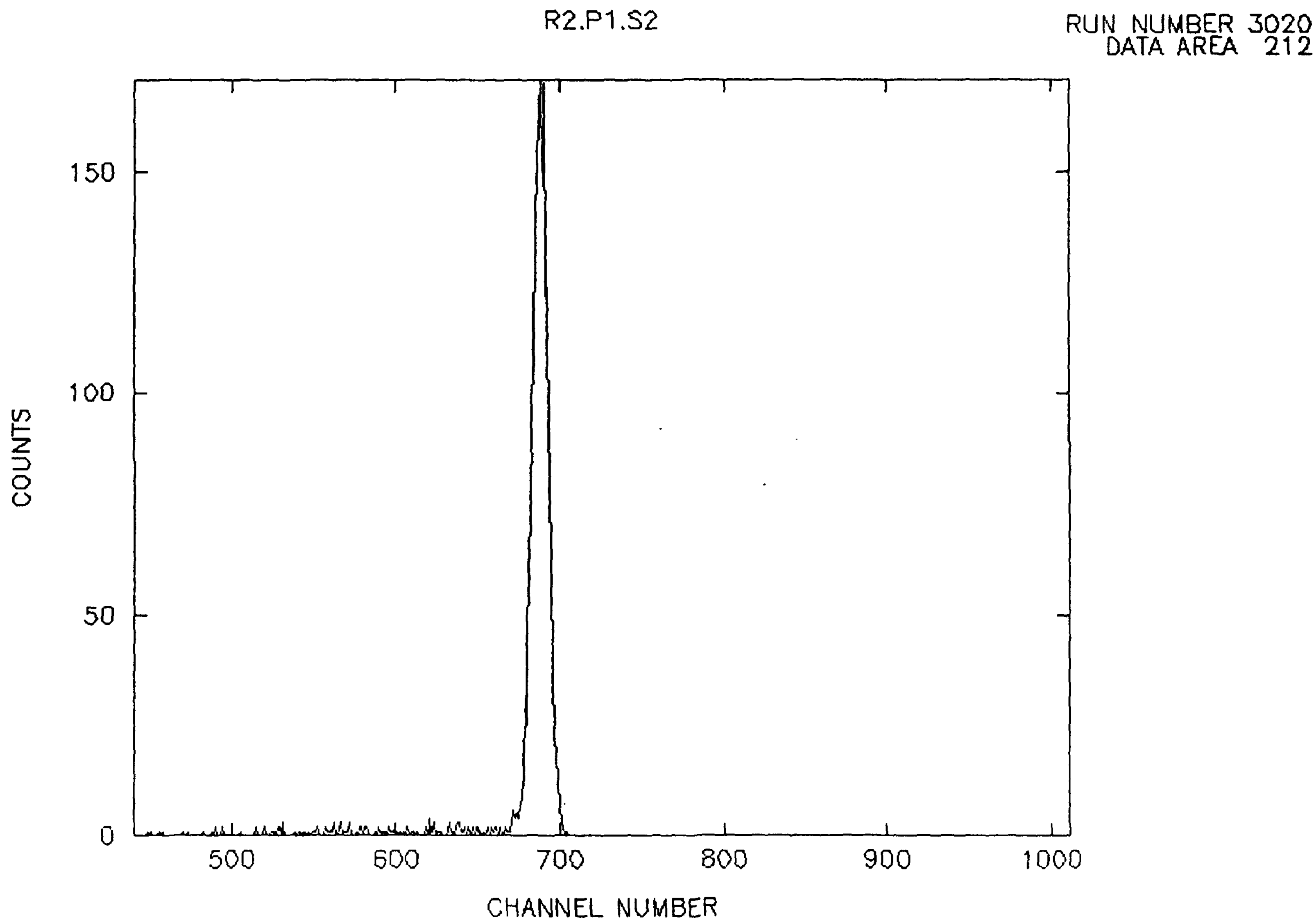

Ta#17 under 4MeV Deuteron Beam on 1OCT
200 nA deuteron beam
for 70 minutes resulted in
a 21% decrease in the ^{3}He
thickness.
Total incident charge
8.2×10^{-4} Coulombs
Implant $*10^{17}/cm_2$
Cumulative BCI ($*10^3$)
1.5
1.3
1.1
0.9
0.7
0.5
0
50
100
150
200
250
300
350

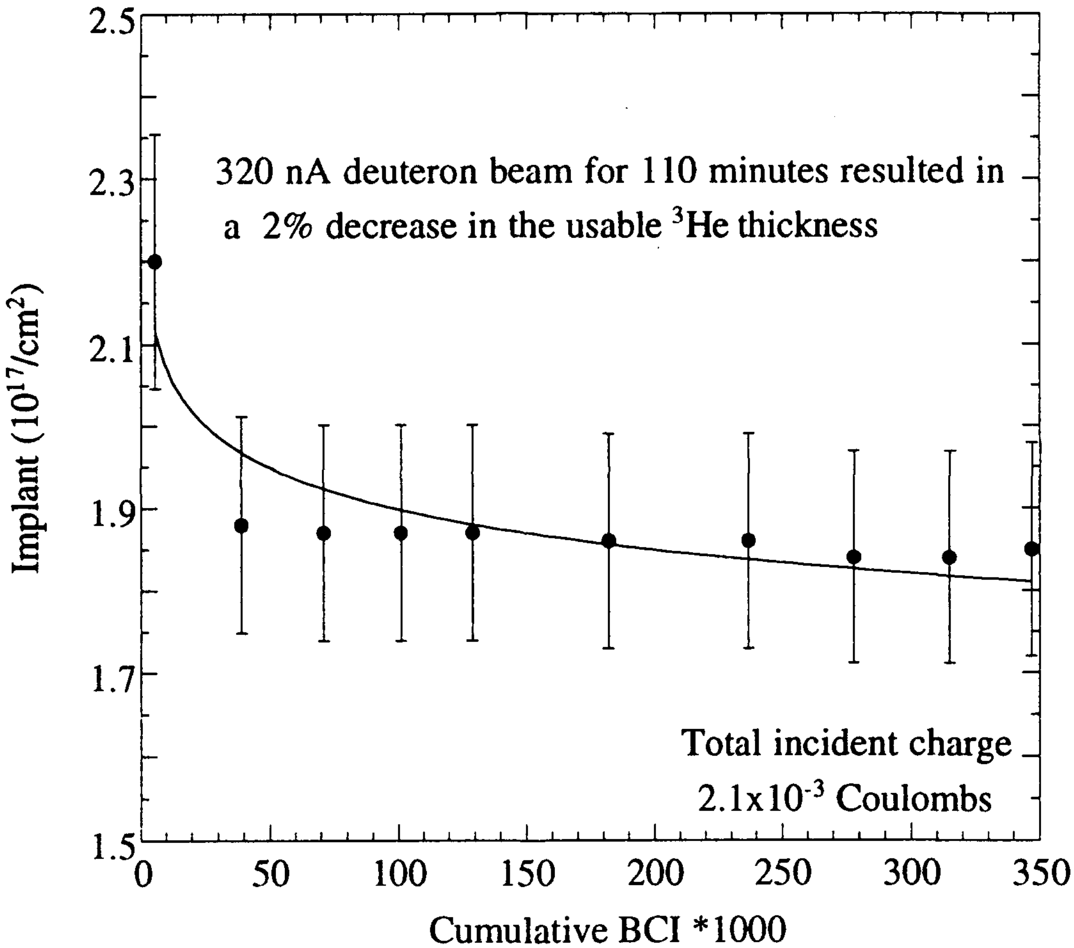
Figure 5



Example spectrum of 222 keV deuterons incident on Ta#24, 9 JAN 94.

Figure 6

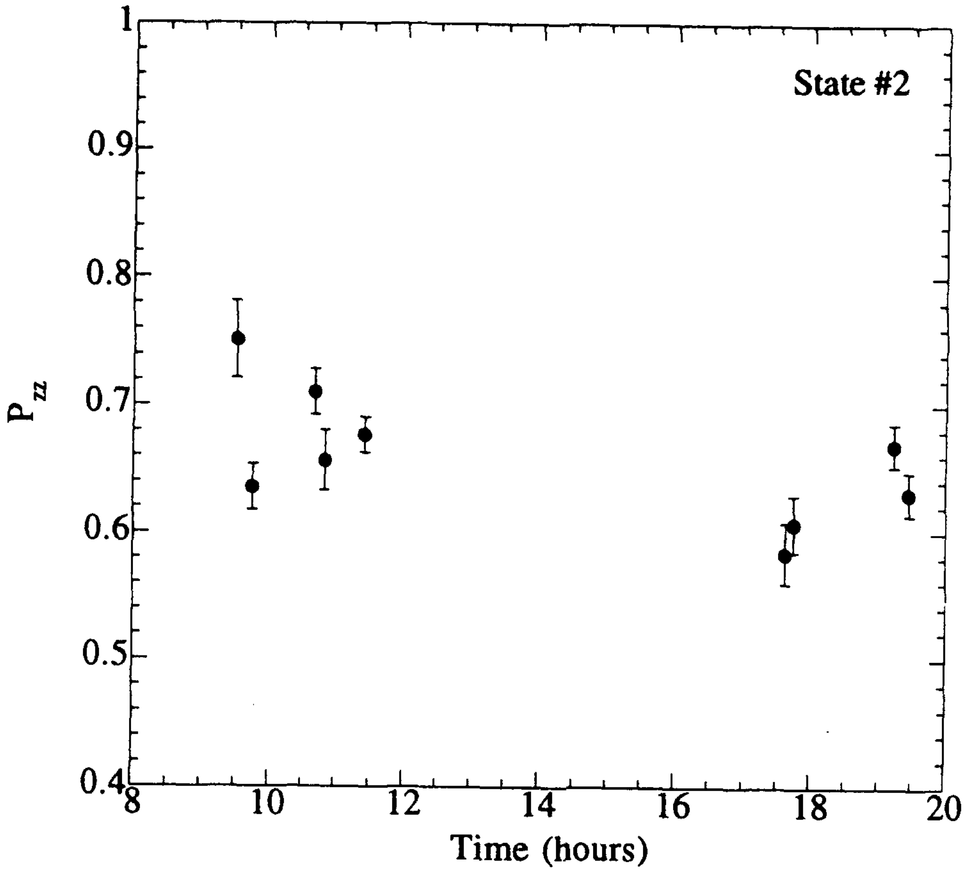
Ta#25 under 322keV deuteron beam 10DEC93



p87 lab notebook #2

Figure 7

Pzz vs. Time on 9JAN94



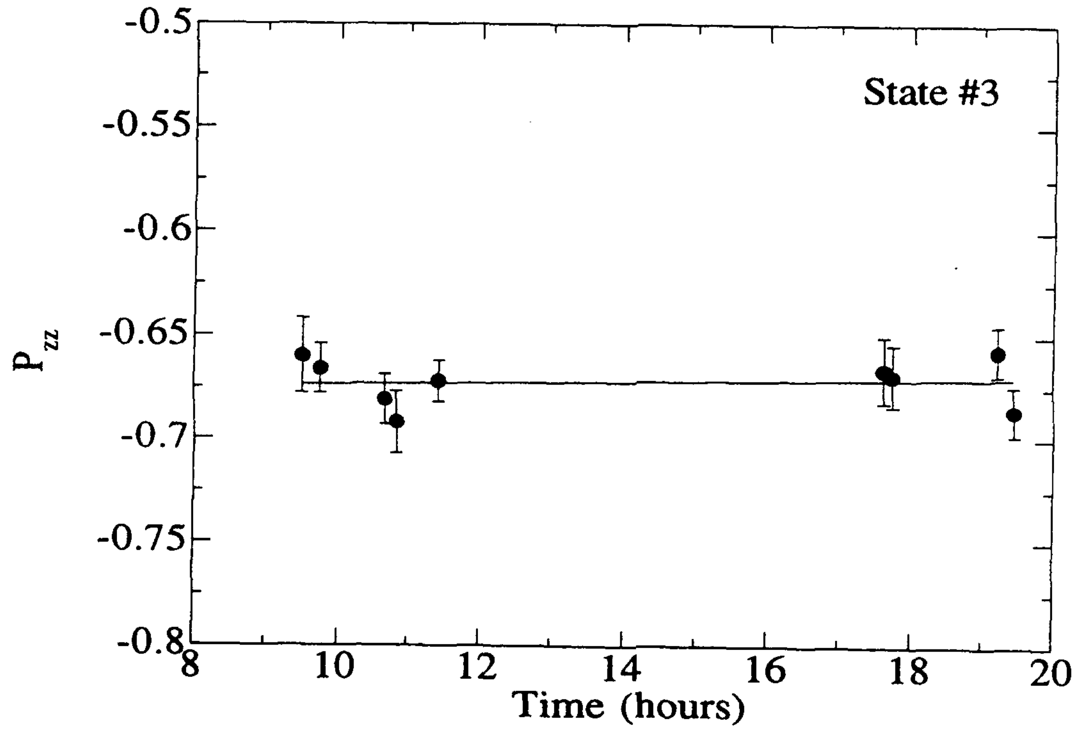


Figure 8

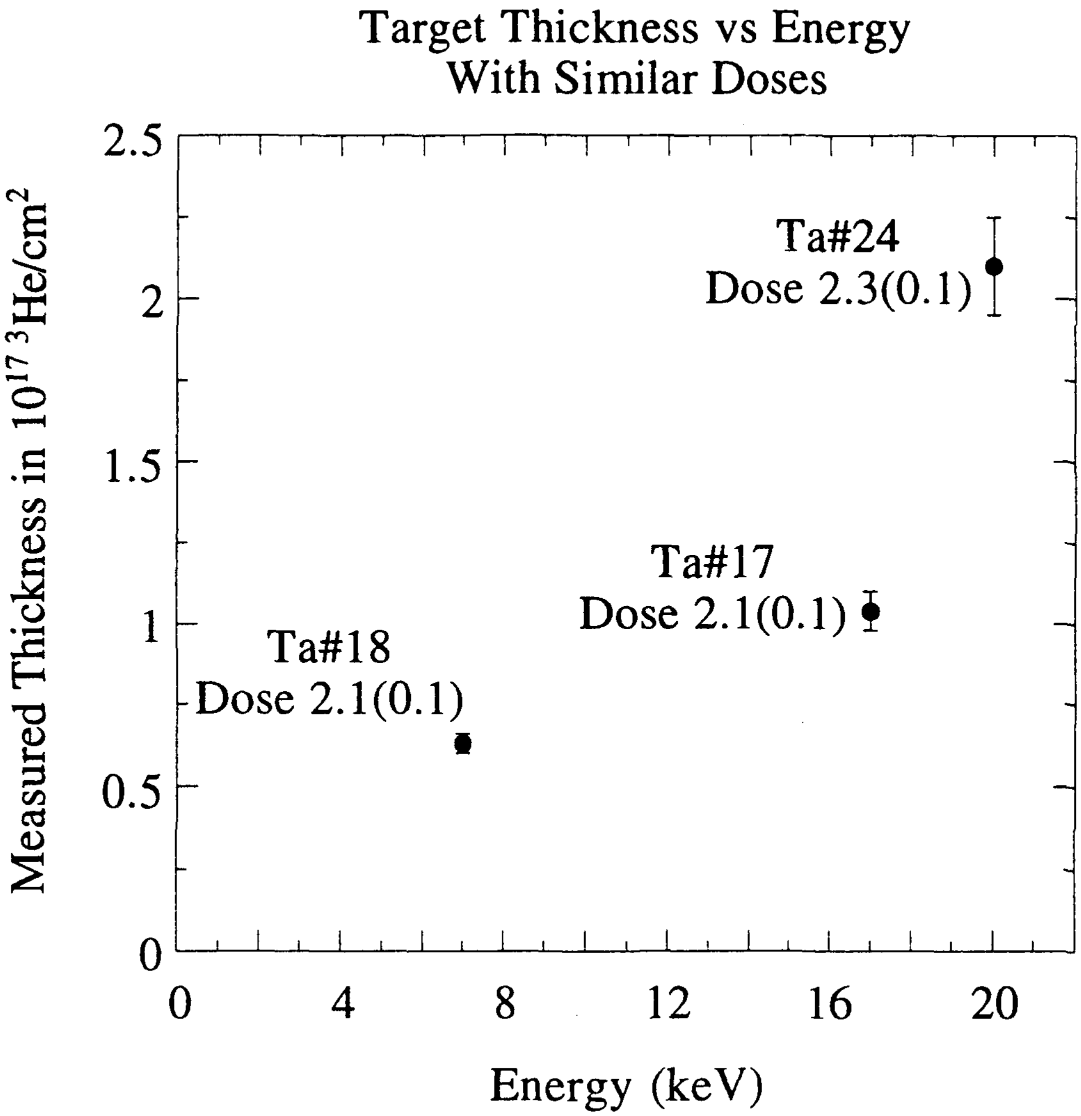

Target Thickness vs Energy
With Similar Doses
Measured Thickness in 10^{17} ^{3}He/cm^2
2.5
2
1.5
1
0.5
0
0
4
8
12
16
20
Energy (keV)
Ta#24
Dose 2.3(0.1)
Ta#17
Dose 2.1(0.1)
Ta#18
Dose 2.1(0.1)

Figure 9

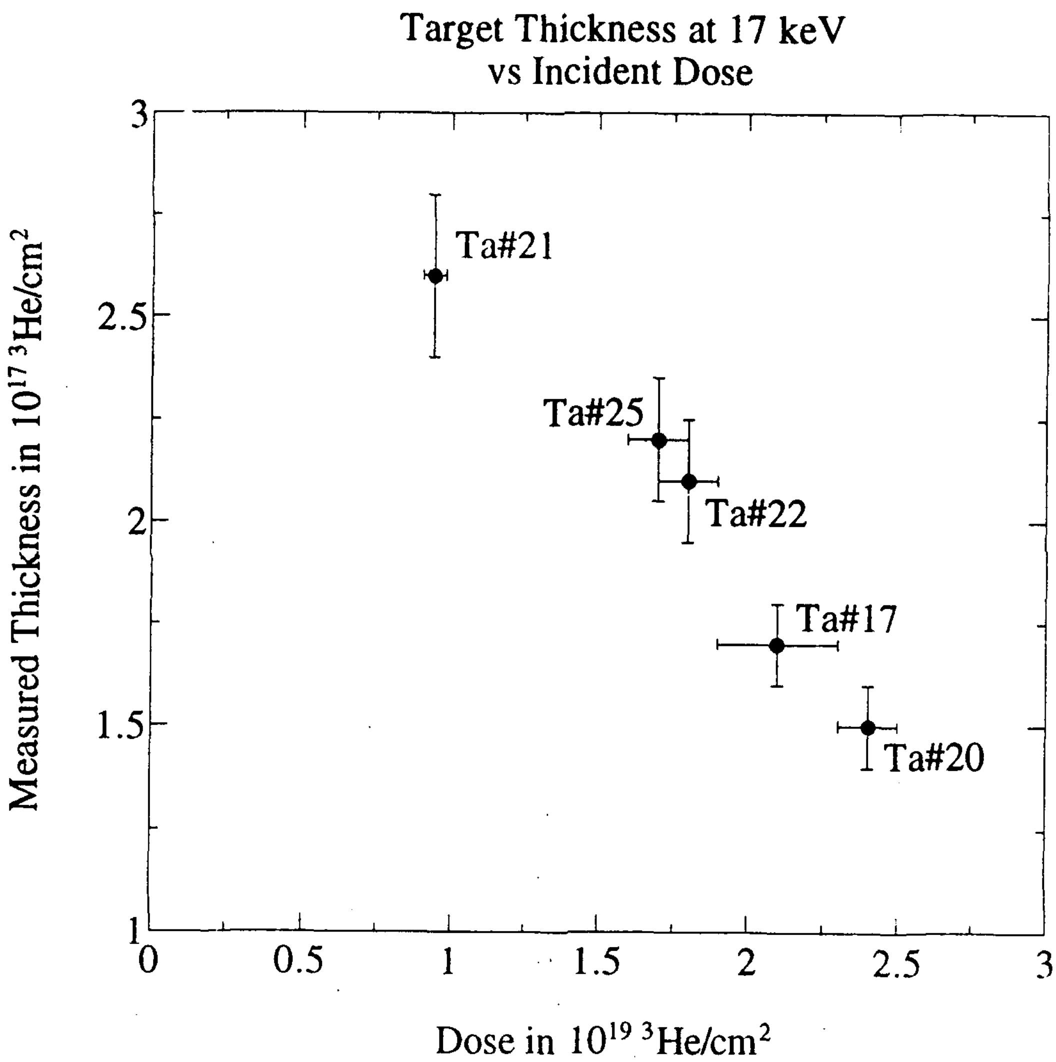
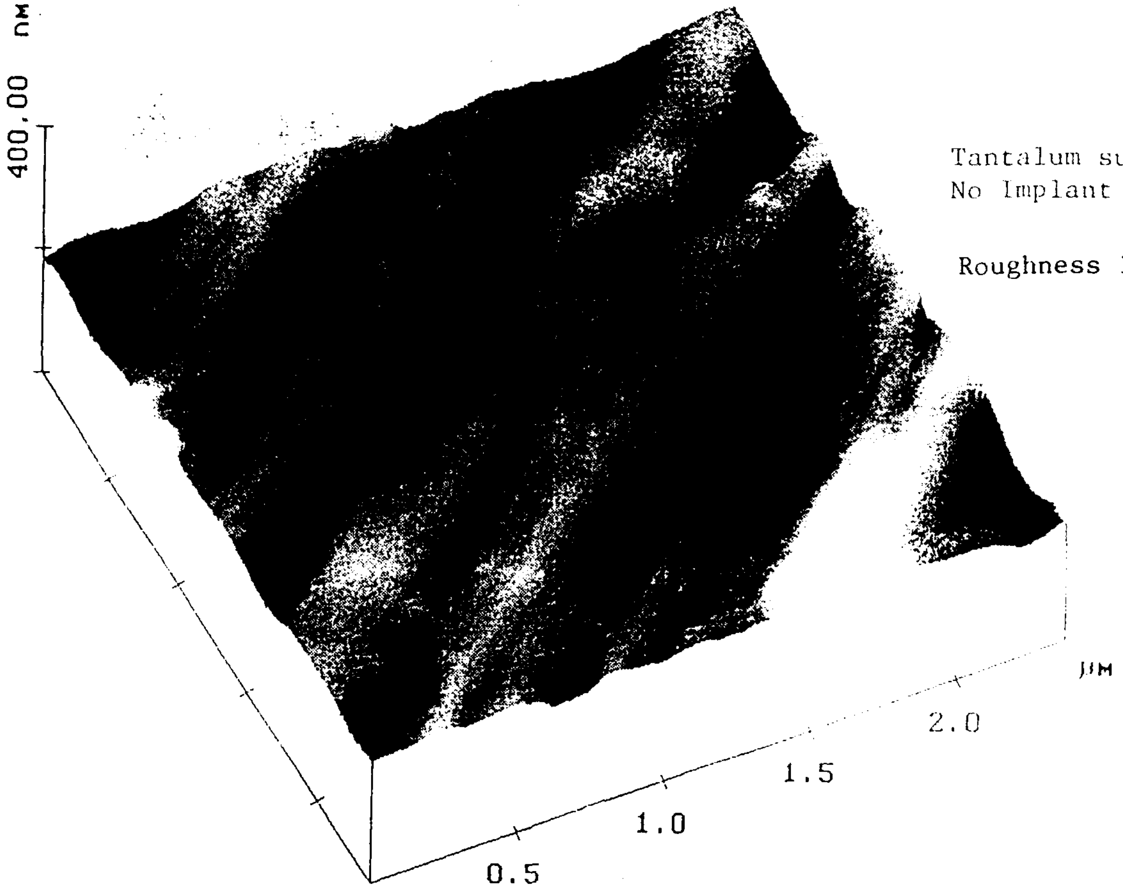
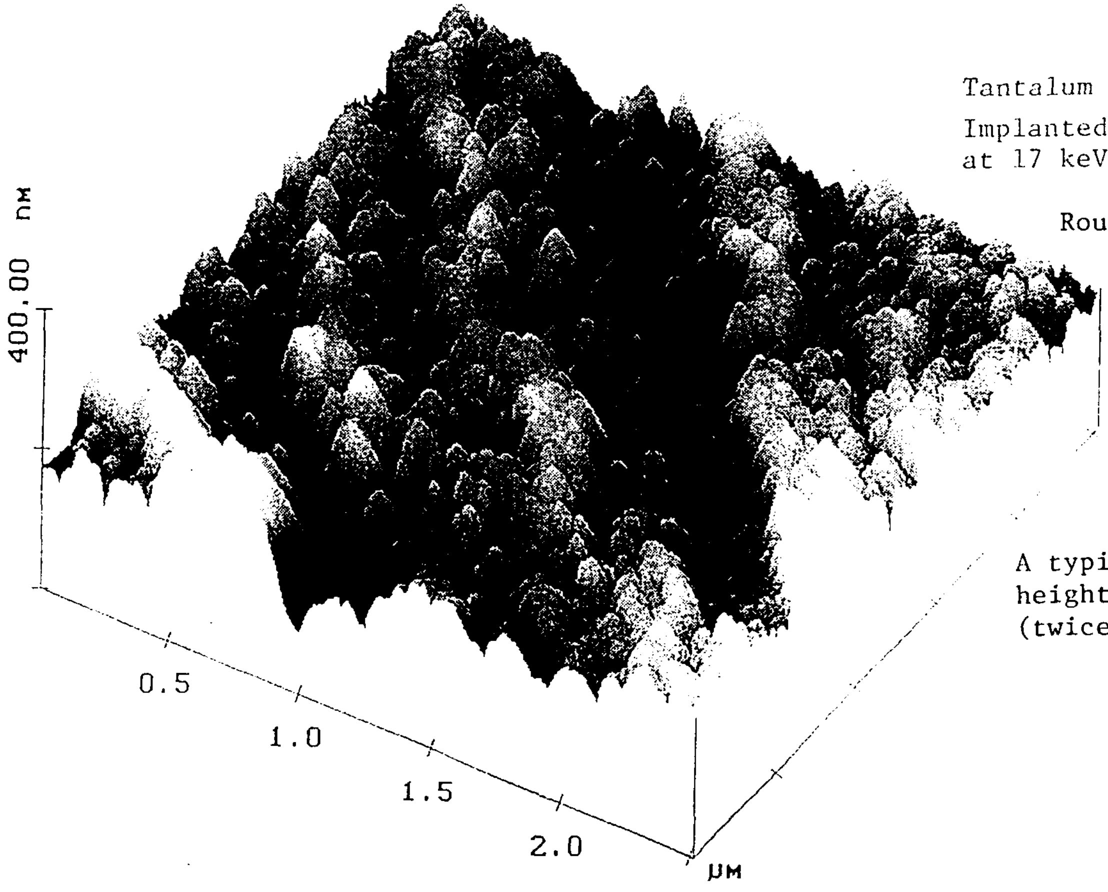

Target Thickness at 17 keV
vs Incident Dose
Measured Thickness in 10^{17} $^3He/cm^2$
Dose in 10^{19} $^3He/cm^2$
Ta#21
Ta#25
Ta#22
Ta#17
Ta#20
3
2.5
2
1.5
1
0
0.5
1
1.5
2
2.5
3

Figure 10



Tantalum substrate
No Implant

Roughness 3 nm



Tantalum substrate
Implanted with ^{3}He ions
at 17 keV

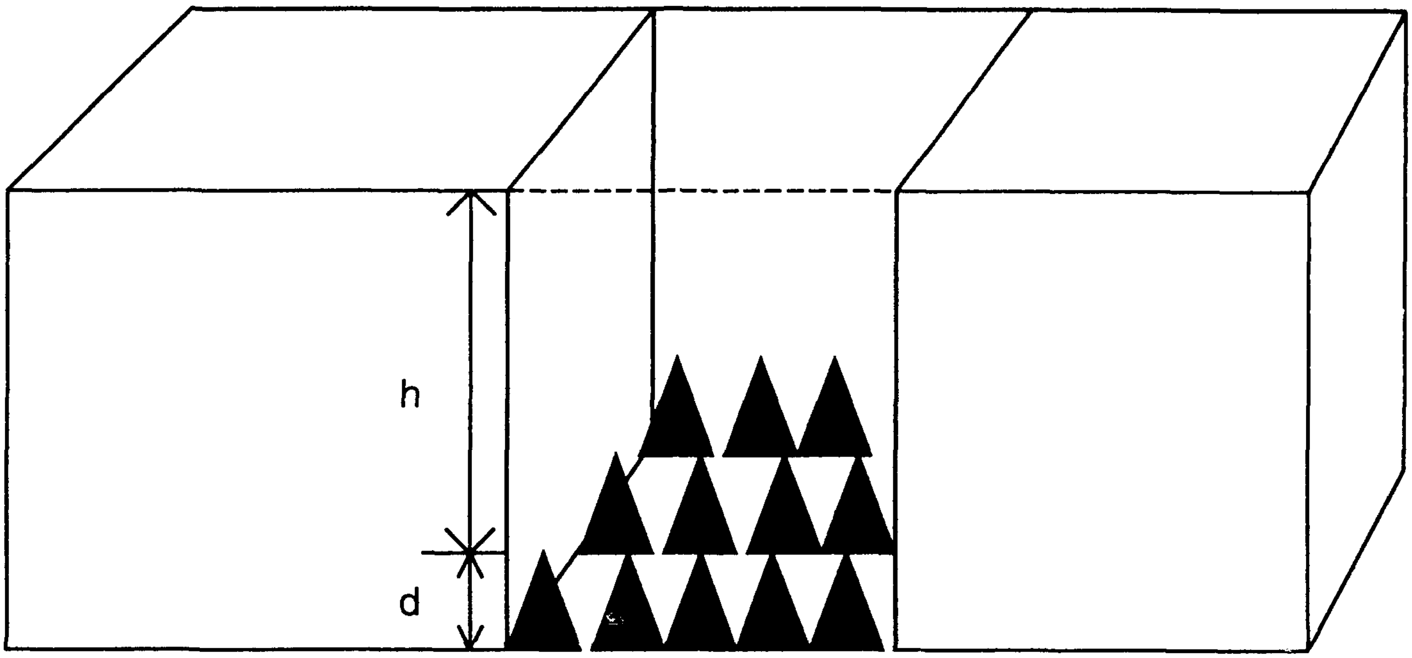
Roughness 20 nm

A typical "mountain"
height is 40 nm.
(twice the roughness)

Nanoscope Images courtesy of Mike Falvo and Dr. Superfine.

Figure 11

Possible 3He Sputtering Cause of the Lack of Retention of 3He Implanted in Tantalum



If the Mass of Ta removed from this cavity is M and the small bumps in the bottom of the cavity account for one half the volume within d of the bottom, then the depth of the well, h, is :

$$h=M/\rho A - d/2$$

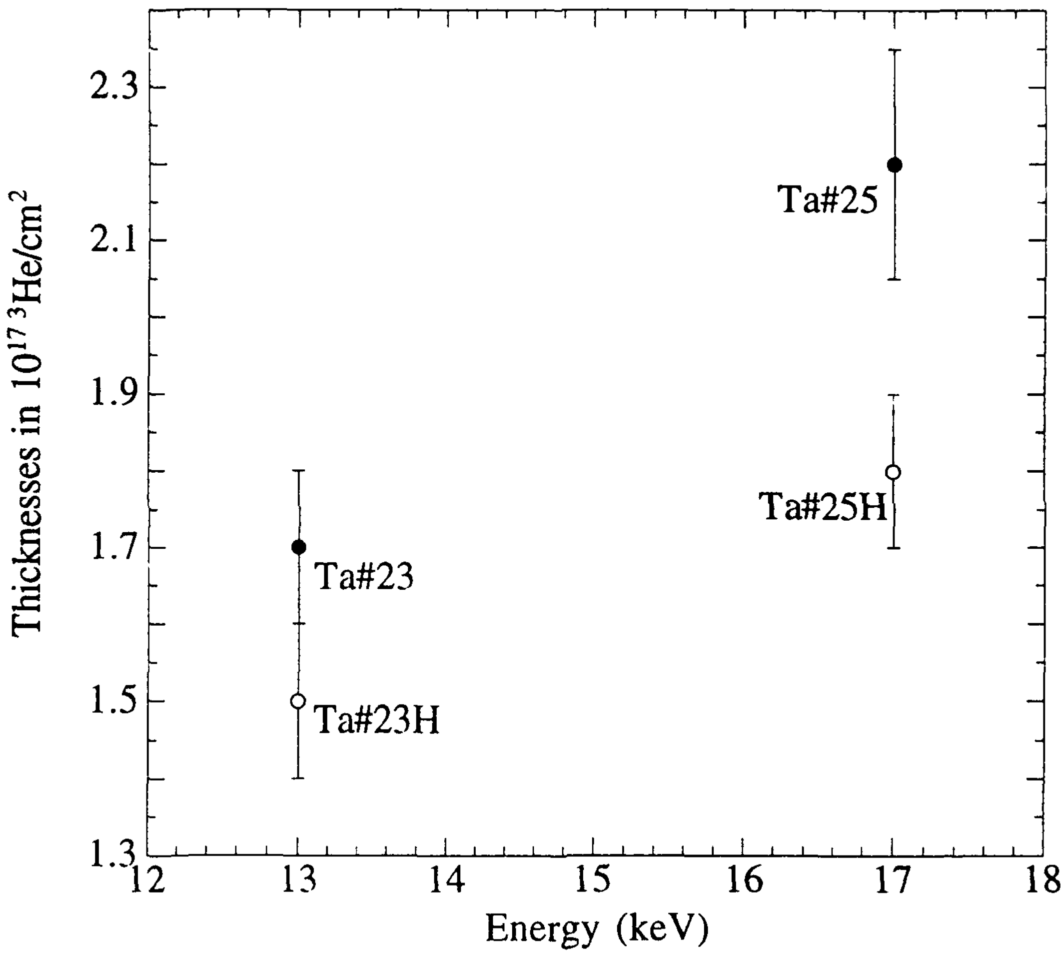
where ρ is the density of Ta 16.6 g/cm2 and A is the area of the cavity.

Target	Area(μm2)	Mass(10^-6 μg)	d(nm)	h(μm)	Range of 4He(μm).
Ta#11 13.3/1.8	0.176	1.3	18	0.4	0.05
Ta#20 17/2.4	0.092	0.2	41	0.1	0.06
Ta#21 17/.94	0.063	0.1	27	0.08	0.06

Note: Ta#21 was the best target produced.

Figure 12

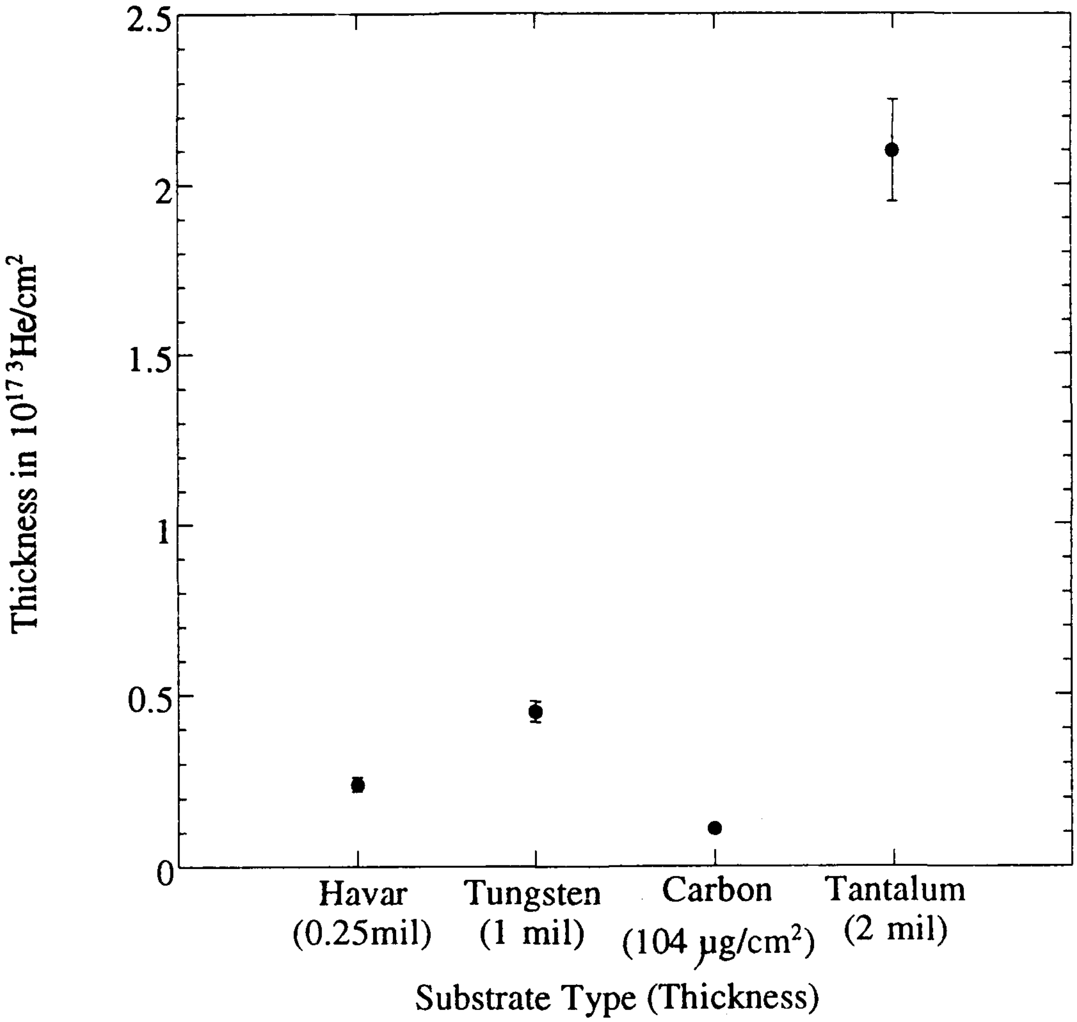
Comparing the Hot and Cool Areas of Two Targets



The Hot targets (H) were the visually glowing part of the substrate during implantation.

Figure 13

Thickness vs Substrate Type
Implanted at 20keV



Note: The substrates were of differing thicknesses which contributed to the difficulty of target cooling and resulted in different practical doses.

Figure 14

Tensor Analyzing Power

$^3He(d,p)^4He$

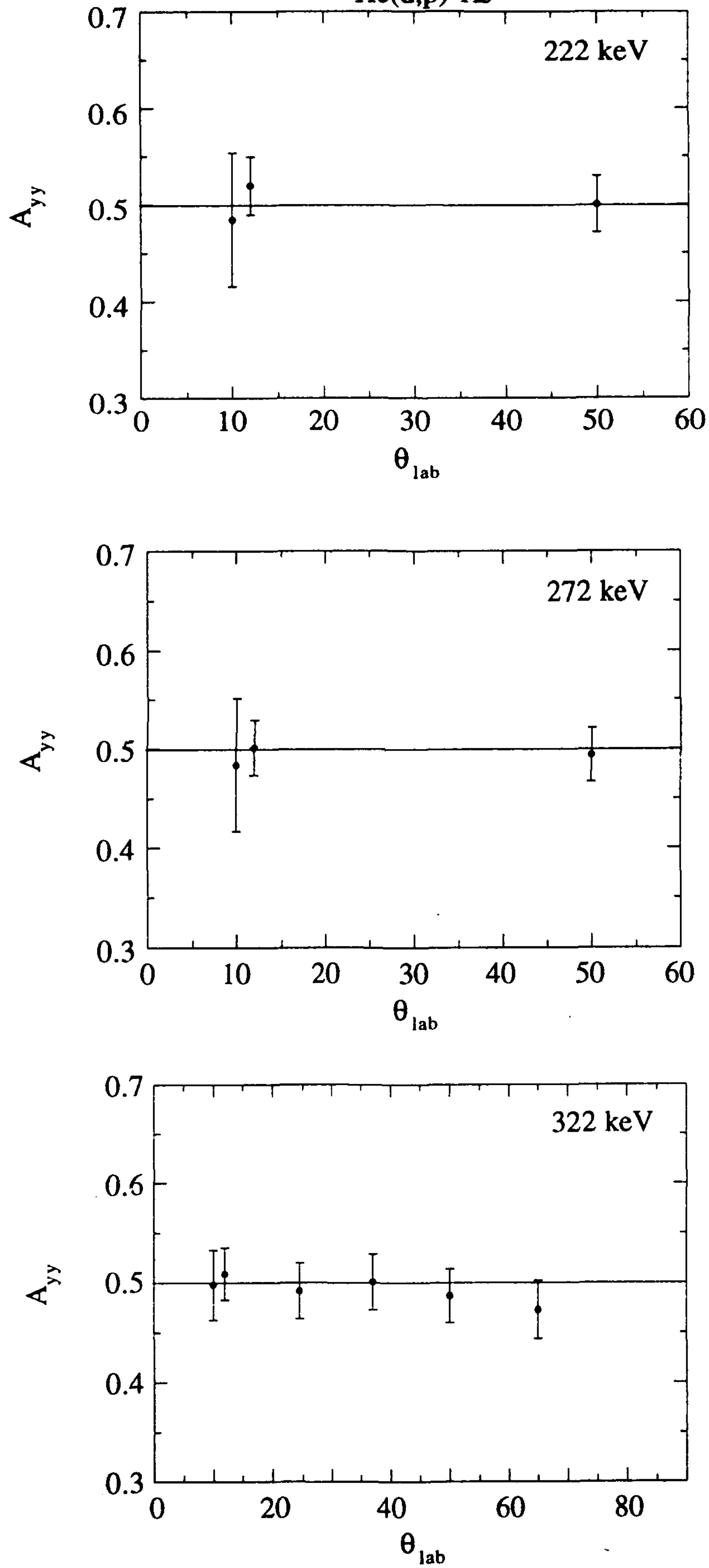


Figure 15

Appendix B

```
/*Last updated 1 July 1993*/
#include<stdio.h>
#include<math.h>
#define MAX 100  /*hopefully there aren't more solutions, Ha! */

main()
/*Computation of Saturation Target Thicknesses*/
{

FILE *fout;
double p, Bohr, F, Mion, Mtarget, E, S, K1, K2, L1, L2, diff;
double Zion, Ztarget, LastValue, PreviousS, R, R1, n, BE, rho, IonRange, W;
double Rsolution[MAX], Rstepped[MAX];
int k, i, j, middle;
char again, NewBE, anotherBE, save;

printf("COMPUTING SATURATION TARGET THICKNESSES OF 3He \n");

/*initialize constants*/
Bohr = 5.291771E-11;  /*Bohr radius in m*/
F = 1.439976E-12;  /*e^2/4piepsilon constant in keV.m*/
Zion = 2.0;  Mion = 3.016029;   /*3He data from Wong*/
Ztarget = 1; Mtarget = 1; E = 1; S = 0;  /*preset values*/
fout = fopen("3HeThickdata","a");

while (Ztarget != 0)
 {
 /*restart  values*/
 i = 0; again = 'y'; NewBE = 'y'; save = 'y'; anotherBE = 'y';

 printf("\nEnter substrate atomic number, mass number,\n");
 printf("and ion energy(keV)--Ztarget, Mtarget, and E  (0 0 0  to end):");
 scanf("%lf%lf%lf", &Ztarget, &Mtarget, &E);
 if (Ztarget == 0)
  {
  printf("\nEnd Program\n");
  exit(0);
  }

 p = 2.0/3.0;
 K1 = Bohr/sqrt(pow(Ztarget,p)+pow(Zion,p));
 K2 = Zion*Ztarget*F*(Mion + Mtarget)/Mtarget/E;
 L1 = 4.24E-7*E*Mion*Mtarget/(Mion + Mtarget)/(Mion + Mtarget);
 L2 = -10.4*sqrt(Mion)/(Mion + Mtarget);

 /*Find R, collisional diameter in meters*/

 for (k=1; k<=10000; k++)
  {
  R = k*1E-14;
```

```
 if (R < K2)
  {
  R1 = K1*log(K2/R);
  diff=fabs(R1-R);
  if (diff < 1E-13)
    {
    i = i + 1;
    Rsolution[i] = R1;
    Rstepped[i] = R;
    }
  }
 } /*for loop*/
/*for solutions that are within 10E-13*/
if (i == 0) printf("Warning!! No solutions found for collisional radius\n");
if (i > 1) printf("Warning!! Multiple solutions for collisional radius\n");
if (i == 1) printf("One solution for collisional radius - Good\n");
for (j=1; j<=i; j++)
 {
 printf("R[%i] = %g    rough R = %g\n",j,Rsolution[j],Rstepped[j]);
 }
middle = i/2;
R = Rsolution[middle];  /*we'll use the middle collisional radius*/
printf("Collisional Radius used => %g\n",R);
/*now find sputtering yield*/
printf("\nEnter target density (atoms/m3):");
scanf("%lf",&n);
while (NewBE != 'n')
 {
 while (anotherBE != 'n')
  {
  printf("\nEnter binding energy BE in eV:");
  scanf("%lf",&BE);
  PreviousS = S;
  S = L1*n*R*R*exp(L2*BE);
  printf("\nWith target BE %lfeV\n",BE);
  printf("Sputtering yield S=%g atoms/ion (PreviousS=%g)\n",S,PreviousS);
  printf("Try a different BE? (y or n):");
  scanf("%s", &anotherBE);
  }
 /*Compute and Present Saturation Thickness*/

 rho = n*Mtarget*1.67E-30;  /*target density in grams/cm3*/
 printf("\nEnter range(cm) of 3He at E = %lfkeV in this substrate:",E);
 scanf("%lf", &IonRange);
 /*Range from LSS projected range theory*/

 W = Mtarget*rho*IonRange/Mion/(S + 1);
 printf("\nIon Saturation Thickness in grams/cm2 is: %g",W);
 printf("\n                    in micrograms/cm2 is: %g",W*1e6);
 printf("\n                     in He atoms/cm2 is: %g",W/Mion/1.67e-24);
 printf("\n\nSave this data? (y or n):");
 scanf("%s", &save);
 if (save == 'y')
  {
```

```
   fprintf(fout,"\n\nINPUT DATA: Implanting 3Helium\n");
   fprintf(fout,"Ion Z= %lf  Implant energy = %lfkeV\n", Zion, E);
   fprintf(fout,"Target Z= %lf   BE=%lfeV   IonRange=%gcm  (4He used)\n",
                                    Ztarget, BE, IonRange);
   fprintf(fout,"\nCALCULATED\n");
   fprintf(fout,"Collisional Radius = %g m  ",R);
   fprintf(fout,"Sputtering yield S = %g atoms/ion\n",S);
   fprintf(fout,"Target density = %lf grams/cm3\n",rho);
   fprintf(fout,"Saturation thickness => %g grams/cm2\n", W);
   fprintf(fout,"                => %g micrograms/cm2\n",W*1e6);
   fprintf(fout,"                => %g 3He atoms/cm2\n",
                                       W/Mion/1.67e-24);
   }  /*stores date in file 3HeThickdata*/
  printf("Recompute with a different binding energy BE? (y or n):");
  scanf("%s", &NewBE);
  } /*while loop*/
 } /*while*/
} /*main*/
```